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Numerical Analysis of Electromagnetic Bandgap Structures

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Introduction: Electromagnetic bandgap (EBG) structures[1] and negative index of refraction (NIR) meta-materials are periodic dielectric or metallic material structures that allow greater control over electromagnetic waves than has previously been possible. Man-made versions of these materials block the propagation of electromagnetic waves within particular frequency bands and allow propagation only in certain spatial directions (Fig. 1). They are scalable and operate over a wide range of frequencies. These qualities are very desirable for a variety of applications such as radar, communication devices, and sensors.

Traditionally, the analysis of the electromagnetic properties of EBG materials relied heavily on the mathematics of infinite periodic structures, similar to that used to describe crystal diffraction. However, for real applications, the finite dimensions, lattice defects, and boundaries have to be included in the analysis to account for their impact on the bandgap characteristics. To accomplish this requires a direct numerical simulation of the finite EBG structure.

We have used a Finite-Difference Time-Domain (FDTD) numerical code to design and characterize EBG structures and to analyze the electromagnetic performance of finite EBG structures at microwave frequencies. This code allows us to directly view the time evolution of the fields in these materials. The FDTD approach is useful for optimization of EBG parameters and can facilitate the design in many emerging applications.

FDTD Method: The FDTD method[2,3] is a numerical technique commonly used in the electromagnetic and optical communities. It is a finite difference solution of Maxwell's differential equations in a bounded computational region. The approach simulates the time evolution of the electromagnetic fields in a spatial volume. It is ideally suited for wave propagation and scattering in complex media and permits visualization of the resulting wave fields as a function of time. Since the computational domain is finite, the method requires the use of absorbing boundaries at the edges of the domain, called perfectly matched layers (PMLs), to permit waves to exit the grid without reflecting back, similar to the absorbing walls of an anechoic chamber.

The FDTD simulations for this work require the use of large parallel computers at various DOD High-Performance Computer (HPC) sites. Our code employs parallel programming techniques based on OpenMP and the Message Passing Interface (MPI) so that very large numerical grids may be used to model electromagnetic phenomena in very large computational domains. Typical simulations may use from 100 million to over a billion FDTD cells and require 8 to 64 processors to model EBG structures in three dimensions.

Simulation of EBG Structures: The Radar Division has used the FDTD method to simulate various EBG structures for possible radar applications. As an example, consider an EBG structure consisting of a hexagonal lattice of dielectric rods made of aluminum oxide with a dielectric constant of 12. By removing two rows of rods from the lattice, a waveguide channel is formed by creating a line defect. The effect of this on the electromagnetic properties of the EBG lattice is that localized modes with propagating frequencies inside the bandgap may exist. Figure 2 shows just this situation where a propagating waveguide mode is created in an EBG lattice. A narrow band pulse is introduced at one end of the defect waveguide. Since the pulse center frequency lies in the forbidden bandgap, no waves may propagate at any angle into the surrounding lattice. The

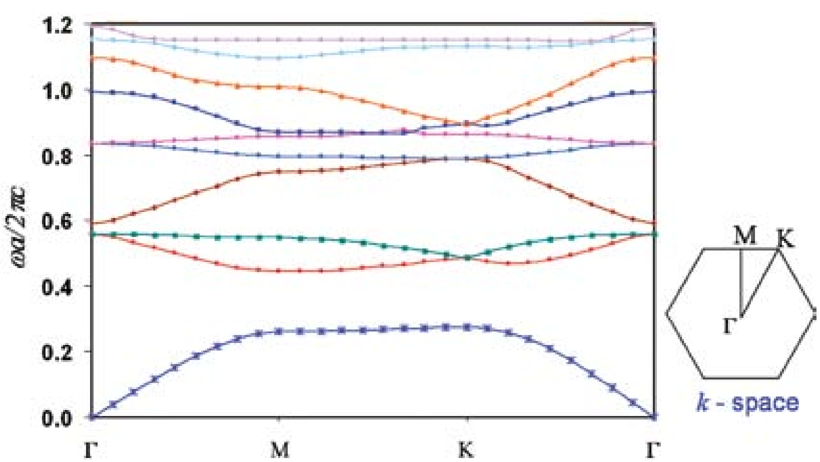

FIGURE 1
Dispersion properties of transverse magnetic (TM) mode in triangular EBG structure made of dielectric rods, $\varepsilon_r = 12$, with radius 0.2 *a* where *a* is the lattice spacing. This structure exhibits both bandgaps and directionally dependent electromagnetic wave propagation.

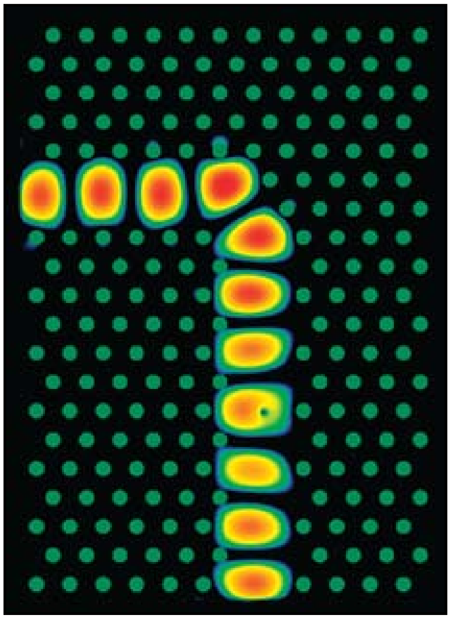

FIGURE 2
EBG waveguide showing a narrow-band transient bending around a sharp corner.

energy is confined, similar to the conventional metallic waveguide. The parameters of the waveguide may be optimized to decrease the losses caused by propagation around a sharp bend.

Other structures are also simulated that are important in controlling microwaves. For example, by removing a circular region and introducing a point defect, a cavity resonator is created. This resonator will have a resonant frequency and quality factor, or *Q* factor, that depends on the size of the cavity and the properties of the surrounding EBG lattice. EBG structures can also be used in antennas as a substrate to suppress surface waves. These surface wave modes tend to degrade the performance of patch antennas. Suppressing these modes is accomplished by introducing a bandgap at the frequency of the surface wave mode.

Left-Handed Materials: Another class of periodic structures or meta-materials that is becoming important in microwave applications is left-handed material (LHM). These materials have a periodic arrangement of scatterers like EBG structures. A LHM that we have modeled is composed of a periodic array of split-ring resonators (SRRs) that produces an effective negative magnetic permeability, and an array of thin wires to provide an effective negative electric permittivity. At frequencies where both the effective permeability and permittivity are negative, the index of refraction will be negative and the group and phase velocities will have opposite signs. Snell's law requires that for negative index materials, refracted waves be bent to the same side of the normal as the incident waves, unlike right-handed materials (RHM), which bend waves to the opposite side of the normal. These unusual characteristics have the potential of enabling LHMs to be used for super lenses, cloaks of invisibility, and filters.

We have modeled a finite array of rectangular SRRs on the top side of a circuit board along with the wires on the opposite side of the board. Figure 3 shows the electric field in a region containing 16 LHM boards of varying length and stacked to form a wedge. Every other board is a wires-only board. Plane waves are incident from the left. Waves leaving the wedge undergo negative refraction since they are bent down from the normal (indicated by the dashed line). The higher amplitude areas in red, over the circuit boards, are indications of resonances in the SRR elements. These simulations illustrate the power of the FDTD method when combined with parallel processing to study electromagnetic wave propagation in complex structures. They will be useful in designing and optimizing unit cell geometry and lattice parameters that determine stop/pass-bands of EBG and other metamaterial structures. This type of research represents an important step towards the use of EBG structures in microwave circuits.

[Sponsored by ONR]

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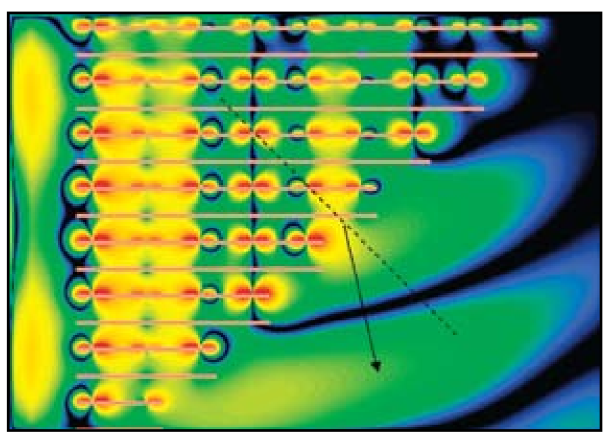

FIGURE 3
Computed electric field clearly showing negative refraction by an LHM wedge.